

## 2. NUCLEAR ROCKETS

By Frank E. Rom, Eldon W. Sams, and Robert E. Hyland

The performance expected of nuclear rockets as determined by materials temperature limits is discussed in this paper. First, nuclear rocket powerplants for use in lifting payloads from the Earth's surface to an Earth satellite will be discussed. Reactors made of various materials will be compared to determine which materials hold the most promise. In addition, the feasibility of nuclear rockets for interplanetary flight will be discussed briefly.

In the previous papers on chemical rockets, the importance of high specific impulse was made clear. Figure 1 illustrates this need for an extended range of specific impulse. The weight breakdown of rockets required for two missions is plotted as a function of specific impulse. The ordinate represents weight expressed as a fraction of the total initial weight. The lower curve represents the Earth to Earth satellite mission. The top curve is the Earth satellite to Mars satellite and return mission. Both missions are single-stage missions. The area above each curve represents fuel weight, while the area below represents the remaining weight available for payload, structure, and engines.

Chemical rockets operating at a specific impulse of about 400 require fuel weights of 90 percent of the initial weight, leaving 10 percent for engines structure and payload. At a specific impulse of 1000 the fuel weight is reduced to 70 percent of the gross weight, thus tripling the weight allowed for engines, structure, and payload. Beyond a specific impulse of 3000, more than 70 percent of the initial weight can be engines, payload, and structure.

In order to obtain high specific impulses, it is desirable to use low-molecular-weight propellants operating at the highest possible temperature. Using fissioning uranium as a heat source, theoretically at least, permits practically unlimited temperatures and in addition permits the free choice of propellant.

Hydrogen, which is the lowest molecular weight element, can be heated by the fission source of energy. The resultant specific impulse of hydrogen as a function of temperature is shown in figure 2. The pressure of the hydrogen before expansion through the nozzle is 100 atmospheres, while the nozzle pressure ratio is considered to be infinite. The upper curve

represents equilibrium expansion, while the lower curve represents frozen expansion. The actual specific impulse will be somewhere between the two curves, depending on the amount of recombination that takes place in the expansion process.

At a temperature of about 6000° F, which is approximately the limit imposed by materials, the specific impulse is about 1000. Beyond this temperature the reactors must be gaseous, and extraordinary methods are required for cooling the walls containing the gas; or else other methods for gas containment, such as by magnetic methods, are necessary.

Figure 3 shows schematically how a nuclear-powered rocket might look. The payload and guidance equipment are located in the nose. A large propellant tank contains the hydrogen in liquid form. A pump pressurizes the hydrogen and circulates it through the walls and other parts of the motor that require cooling. The hydrogen then is heated in a nuclear reactor and expanded through a nozzle to produce thrust.

The first case considered is that in which the hydrogen is heated by contact with solid materials containing fissioning uranium. Figure 4 shows a schematic drawing of such a system. The heart of the system is a nuclear reactor, which contains uranium in some solid form. The core, composed of a moderating material, is pierced with passages to permit the hydrogen to flow through and be heated. A neutron reflector with coolant passages is indicated around the sides of the core. A pressure shell surrounds the core and reflector. Thermal shielding is provided inside the pressure shell to reduce the gamma heating in the walls. Further gamma shielding is provided outside the shell in the direction of the pump and propellant tank to minimize heating in the pump and in the propellant. This shield also protects the payload, guidance equipment, and human beings from direct radiation. The pump to the right pressurizes the hydrogen and circulates it through the nozzle walls, the reflector, and along the thermal shield and pressure shell walls for cooling purposes. The hydrogen flows through the reactor where it is heated. The hot hydrogen then expands through the nozzle.

The key to obtaining high specific impulse is the use of the best possible high-temperature materials. Figure 5 shows approximate maximum operating temperatures for various materials that might be used in the reactor core. The first group of three materials represents moderating materials. Beryllium could be operated at 1700° F, beryllium oxide at 3300° F, and graphite at 5000° F. The reactor core could be made of these materials with uranium in some suitable compound dispersed throughout. The heat of the fissioning uranium would thus be generated directly within the moderator. Holes piercing the moderator would heat the hydrogen flowing through them. Beryllium and beryllium oxide are better moderators than graphite and should yield smaller reactors for a given propellant flow. Graphite, however, would produce higher temperatures. The relative importance of high temperature and small reactor size is discussed later.

On the right in figure 5 are listed structural materials that might be used as fuel elements if it is desired to contain uranium in metallic materials instead of dispersing it in the moderator. The nickel-base materials, which are fairly well developed, can be expected to operate at temperatures up to 2000° F. Molybdenum-base alloys, which have had little development work thus far, may be expected to reach temperatures approaching 4000° F. The tungsten-base alloys, about which very little is known at present, may some day reach 5500° F. The highest melting materials known, hafnium carbide and tantalum carbide, may someday provide operating temperatures of around 6000° F.

In the subsequent discussion the performance of graphite and beryllium oxide reactors with uranium dispersed in the moderator itself is examined first. Then reactors that use the better moderating materials as moderators and contain the uranium in fuel elements made of molybdenum and tungsten are considered. The mission that will be used as the basis of the comparison is the carrying of large payloads from the Earth's surface to a satellite orbit about the Earth.

The discussion of the performance that can be obtained from a given reactor will be based on the reactor shown in figure 6. The core is composed of uranium-impregnated graphite with holes piercing it for passage of the hydrogen. The core diameter is 3.5 feet and length is 2.8 feet. The flow area represents 30 percent of the frontal area of the core. The reflector chosen is a 6 inch-thick beryllium reflector. This reflector material and thickness result in about the minimum core-plus-reflector weight for the given hydrogen flow area desired. The uranium investment is about 77 pounds.

In the operation of this reactor, the operating temperature level, the hydrogen flow velocity, and the pressure level may be selected. The temperature is determined by materials limitations. The best hydrogen flow velocity, which is a result of performance calculations, is that value which gives very near choking conditions at the reactor exit. In all the subsequent calculations the best hydrogen velocity will be used.

The choice of the best pressure level is illustrated in figure 7. The effect of hydrogen pressure on powerplant weight and thrust per engine weight for a maximum surface temperature of 5000° F is shown. The powerplant weight includes the reactor core and reflector shown in figure 6, and also the pressure shell, nozzle, turbopump unit, and shielding necessary to reduce heat generation in the pressure shell and in the propellant. The shielding also affords protection from direct radiation to the payload, guidance equipment, and human cargo. The increase in powerplant weight with pressure is due to the increase in pressure shell, nozzle, and turbopump weight with pressure level. The thrust per powerplant weight ratio increases with pressure level in spite of the increased powerplant weight because of the overriding effect of the thrust increase.

At a pressure level of 1200 pounds per square inch, the thrust to powerplant weight ratio is 30, and the powerplant weight is about 17,000 pounds.

Figure 8(a) shows the performance that can be expected of this same rocket motor as a function of pressure. The mission is to establish a satellite about the Earth with a single-stage vehicle. The thrust-to-gross-weight ratio chosen is 2.0, which is about best as determined by a series of calculations. The payload and gross weight both increase with increasing pressure, reflecting the increase in thrust due to the pressure increase. At a pressure of 1200 pounds per square inch with an initial gross weight of 260,000 pounds, it is possible to carry a payload of 20,000 pounds to a satellite.

In the next case, the gross weight is held constant at 300,000 pounds. The thrust and hydrogen flow required are constant, so that increasing pressure reduces the required reactor size. The reactor diameter and payload are plotted in figure 8(b) as a function of pressure for the Earth satellite mission. The reactor diameter decreases as shown, from about 4.1 feet to about 3.2 feet when the pressure is increased from 800 to 2000 pounds per square inch. The payload increases from about 20,000 to 25,000 at 1300 or 1400 pounds per square inch, and then decreases slightly beyond this pressure. An optimum pressure is indicated, but the curve is quite flat. The reason the payload curve shows an optimum is as follows: At first, the reduction in core size reduces the powerplant weight, giving a higher payload. As pressure increases further, the increase in pressure shell, nozzle, and turbopump weight is more important than the reduction in core weight, and the payload weight decreases.

The operating pressure to be selected, then, does not come from calculations such as these. The pressure is determined by practical limitations such as (1) the problem of pumping cryogenic fluids to very high pressures and (2) the problem of designing cooled pressure shells with internal gamma heat generation.

The discussion thus far has been based on the use of uranium-impregnated graphite as the reactor core material. It might be suggested that beryllium oxide should be used in place of graphite, since it is a much better moderating material than graphite. The use of beryllium oxide would reduce the required core size for a given hydrogen flow. However, since the operating temperature is much lower for beryllium oxide, the specific impulse would be less.

The powerplant weight and thrust per powerplant weight for graphite and beryllium oxide reactors with dispersed uranium are plotted as a function of hydrogen flow rate in figure 9 for a pressure of 1200 pounds per square inch. The beryllium oxide reactors operate with a maximum surface temperature of 3300° F with a specific impulse of 645 seconds. The

graphite reactors operate with a maximum surface temperature of 5000° F and with a specific impulse of 816 seconds. The graphite reactors are about 50 percent heavier than the beryllium oxide reactors because of the superior nuclear characteristics of beryllium oxide. The fact that the specific impulse is lower for the beryllium oxide does not overcome the lower weight advantage, as shown by the higher value of thrust per powerplant weight for beryllium oxide. On the basis of thrust per powerplant weight ratio, beryllium oxide would appear to be the better propulsion system.

In considering a rocket vehicle, the specific impulse must also be taken into account. Table I shows the performance of Earth to Earth satellite rockets using the dispersed-uranium graphite and beryllium oxide reactors of figure 9. Reactor sizes were chosen to obtain the thrust required for a 300,000-pound-initial-weight single-stage rocket. The maximum surface temperature and specific impulses are again noted for the beryllium oxide and graphite reactors. The beryllium oxide powerplant has a thrust to powerplant weight ratio about 30 percent greater than the graphite powerplant, but has a 20-percent-lower specific impulse. The net effect is that the payload of the beryllium oxide system is about 60 percent less than the payload for the graphite reactor. Thus, it may be concluded that, if reactors in which the uranium is dispersed throughout the moderator are to be used, graphite is the better material to use.

The use of beryllium oxide results in very substantial powerplant weight savings. In order to take advantage of this, the uranium must be removed from the moderator and placed in high-temperature materials fabricated into fuel elements. The high-temperature fuel elements then heat the hydrogen. The moderator must be cooled in this case. A schematic picture of one such system is shown in figure 10. The rocket motor pictured is similar to the previous one in all respects except that the core arrangement is different. The uranium is contained in high-temperature materials such as molybdenum or tungsten fabricated into flat plates, concentric sheets, or tube bundles. The elements are located in holes in the moderator. The hydrogen first passes from left to right in the annular gap between the hole and the fuel element. During this passage the heat generated in the moderator is picked up. The flow is then reversed and passes through the fuel element, which heats the hydrogen to the desired operating temperature. Because of the two coolant passes required, the flow area required in the reactor is about 20 percent larger than the once-through flow area, assuming that 5 percent of the heat produced is generated in the moderator. This penalty is included in all subsequent calculations for cooled-moderator reactors.

Figure 11 shows the performance expected with beryllium as the moderator and tungsten or molybdenum as the fuel-element material. Beryllium was chosen in place of beryllium oxide because its moderating ability is about the same as beryllium oxide but its density is lower, resulting

in a lighter reactor. The powerplant weight and thrust to powerplant weight ratio are plotted as functions of hydrogen flow. The pressure level is again 1200 pounds per square inch. The dispersed-uranium graphite reactor is shown for reference. The tungsten fuel elements are assumed to operate at a maximum surface temperature of 5500° F, which produces a specific impulse slightly greater than that for the graphite reactor. The molybdenum fuel element operates at a maximum temperature of 4000° F and produces a specific impulse of 715 seconds.

The powerplant weights for the beryllium reactors are about 30 to 50 percent lower than the graphite reactor weights. The tungsten reactor is slightly heavier than the molybdenum reactor, because the hydrogen requires a larger flow area with tungsten, since the hydrogen is at a higher temperature. The thrust per powerplant weight for the beryllium reactors is about 40 percent higher than for the graphite. The value for the tungsten reactor is higher than for the molybdenum reactor, because the higher specific impulse more than offsets the slightly greater weight of the tungsten reactor.

Thus, using a cooled beryllium moderator increases the thrust per powerplant weight of the rocket engine. Using tungsten for the fuel-element material increases specific impulse. Both of these effects should give better rocket performance.

Table II shows the performance expected of tungsten-beryllium and molybdenum-beryllium reactors compared with that of the dispersed-uranium graphite system. The comparison again is made for the Earth satellite mission with a 300,000-pound-initial-weight single-stage rocket. The thrust to powerplant weight ratio is about 25 percent higher for both beryllium-moderator systems than for the graphite system. This, coupled with higher specific impulse of the tungsten system, increases the payload from 28,500 pounds for the graphite system to 38,000 pounds for the tungsten-beryllium system. The molybdenum system has a payload about 25 percent less than the graphite system.

If it is desired to carry men to an Earth satellite, additional shielding would be required for protection against scattered radiation in passing through the Earth's atmosphere. Shielding against direct radiation is already provided for in the powerplant assembly weight. Approximately 35,000 pounds of additional shielding and equipment is required for a load of four men. This mission could be accomplished with the tungsten-beryllium reactor for the gross weight of 300,000 pounds. The graphite reactor would require a somewhat larger gross weight (about 350,000 lb).

It appears that ultimate nuclear rocket performance may come from the use of tungsten-base fuel elements in conjunction with good moderator materials that are cooled. The gains indicated are sufficient to warrant a closer look at the problems of such a reactor system for nuclear rocket propulsion.

There are additional advantages in using metallic fuel elements. Should it be desirable to design nuclear rocket systems for reuse, for example as a ferry from the Earth to an Earth satellite and return, it would be necessary to contain the fission products and uranium. Metallic fuel elements can contain these materials better than ceramic or graphite elements and therefore should be of greater interest. In addition, the metallic fuel elements are advantageous in that they are not attacked by hydrogen and so would not require protective coatings as is necessary with graphite. The disadvantage, of course, is the added complication of a cooled moderator.

The technology of molybdenum and tungsten is in its infancy, and a great deal of research is necessary to develop satisfactory alloys for operation at the temperatures indicated and also to learn how to fabricate and form these materials into reliable fuel elements.

Thus far, only an Earth to Earth satellite mission has been discussed. Now the possibility of using nuclear rockets for interplanetary flight will be considered. As will be pointed out in the next paper, high thrusts are not required to achieve flights to the moon or to Mars if the vehicle starts from an Earth satellite. High specific impulses are important, however.

It is possible to increase the specific impulse of nuclear rockets by operating them at lower pressure levels, because hydrogen can be dissociated into hydrogen atoms more readily at lower pressures. This is shown in figure 12, where specific impulse is plotted as a function of hydrogen temperature and pressure. In the range of 5000° F or higher, large increases in specific impulse are possible by reducing the pressure from 100 to about 1 atmosphere. For example, at a temperature of 5000° F the specific impulse can be increased from about 900 seconds at 100 atmospheres to about 1100 seconds at 1 atmosphere and to about 1400 seconds at 0.01 atmosphere.

To illustrate the use of low-pressure nuclear rockets for interplanetary flight, a mission to Mars from an Earth satellite and return to the Earth satellite will be considered. The mission consists in sending an eight-man exploring party to Mars with equipment for surface exploration of Mars. This mission will be described in greater detail in the next paper.

The reactor will be the same type as used for the satellite mission. Two beryllium-tungsten reactors that normally produce 800,000 pounds of thrust each at a pressure level of 1200 pounds per square inch will be operated at pressures of about 2 or 3 atmospheres. The weight of two of these powerplants would be about 40,000 pounds.

The performance expected for the Mars trip for specific impulses of 1000 and 1200 seconds is shown in table III. The required initial gross weights are 620,000 and 520,000 pounds, assuming that the required velocity changes occur instantaneously. Gas temperatures of 5000° and 5700° F with reactor pressures of 3.3 and 2.3 atmospheres, respectively, produce thrust equal to 10 percent of the gross weight, which then would give an acceleration of 0.1g. Taking into account the fact that the thrust is not applied instantaneously would increase the gross weights somewhat. The reactor powers are 1200 and 1700 megawatts, respectively.

This Mars mission starts from an Earth satellite. In order to assemble the vehicle for the Mars journey, about 600,000 pounds of fuel and equipment must be placed in this satellite orbit by rockets from the Earth's surface. Nuclear rockets such as the 300,000-pound-gross-weight beryllium-tungsten rocket described earlier can be used. Each of these can carry a payload of 38,000 pounds. It would therefore take 15 trips to carry the fuel and equipment. An additional two trips would be necessary to place the eight men with shielding into the orbit.

Temperatures of 5000° and 5700° F are within reason with the use of tungsten or the carbides of hafnium and tantalum. It is easier to obtain these temperatures with low-pressure operation than at the high-pressure condition because of two effects. First of all, the reactor is operating at a lower power level, about 1/8 or so of the power at full pressure. This means that the temperature difference within the fuel element will be lower, so that the surface can be operated at a higher temperature without danger of melting the center. In addition, hot spots that develop owing to imperfections in the reactor construction will have a greater heat-removal rate, since the hydrogen will be dissociating at a greater rate at the hot spot. Dissociation, then, will tend to make temperatures more uniform throughout the reactor and thus increase the chances of obtaining higher gas temperatures.

It seems, then, that interplanetary travel with nuclear rockets limited to temperatures imposed by materials gives reasonable performance as indicated by gross weights in the range of 600,000 pounds for the Mars trip.

Further increases in performance can be obtained by going to higher specific impulses. The temperatures required, however, are beyond materials capabilities. In this temperature range and higher, the fissioning uranium must be in the gaseous phase and the heat must be transferred directly to the propellant. Several organizations are investigating methods of obtaining these ends. The NACA is investigating the possibility of heating hydrogen directly with fissioning uranium in gaseous form in the so-called cavity-type reactors. The chief problem is determining methods for preventing the uranium from escaping with the hydrogen. The use of centrifugal fields and magnetic fields for uranium retention is being studied.

Another problem is the determination of the heat transferred by radiation from the gas mixture to the walls. In addition, the calculations of the criticality of cavity reactors is receiving some attention so that the required uranium concentration and power generation distributions can be determined.

In conclusion, nuclear rockets can be expected to carry payloads of about 10 to 13 percent of the initial gross weight to an Earth satellite. The nuclear rocket shows promise of Earth satellite to Mars and return interplanetary flights with initial gross weight within reason. This flight can be accomplished by reducing operating pressure so that dissociation effects can result in high specific impulses.

The use of nuclear energy as a heat source in heat-transfer rockets as presently conceived does not even begin to use the ultimate potential of the fission process. New ideas and concepts are required to utilize the full potential of nuclear energy for rocket propulsion.

# ROCKET PERFORMANCE COMPARISON

FUEL ELEMENT, COOLED MODERATOR TYPE,  
EARTH SATELLITE MISSION; PRESSURE, 1200 PSI,  
INITIAL GROSS WT, 300,000 LB

	Be-W	Be-Mo	GRAPHITE
MAX SURFACE TEMP, °F	5500	4000	5000
SPECIFIC IMPULSE, SEC	855	715	816
THRUST TO POWERPLANT WEIGHT RATIO	38.0	37.6	30.0
PAYLOAD, LB	38,000	21,000	28,500
REACTOR POWER, MW	12,700	10,800	12,000

CS-14743

Table II

# ROCKET WEIGHT BREAKDOWN

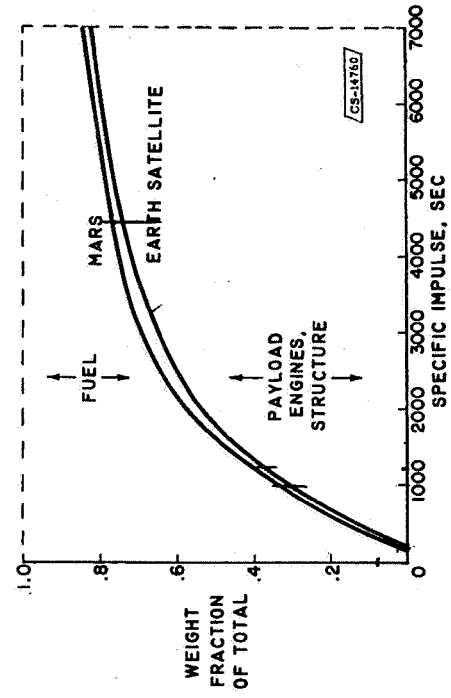


Figure 1

# ROCKET PERFORMANCE COMPARISON

DISPERSED URANIUM REACTORS, EARTH SATELLITE MISSION  
PRESSURE, 1200 PSI, INITIAL GROSS WEIGHT, 300,000 LB

	BeO	GRAPHITE
MAX SURFACE TEMP, °F	3300	5000
SPECIFIC IMPULSE, SEC	645	816
THRUST TO P.P. WT. RATIO	38.5	30.0
PAYLOAD, LB	11,000	28,500
REACTOR POWER, M	9800	12,000

CS-14741

Table I

# LOW PRESSURE NUCLEAR ROCKET

FUEL ELEMENT, COOLED MODERATOR TYPE, MARS MISSION  
ENGINE WT, 40,000 LB, THRUST TO INITIAL WT, 0.1

SPECIFIC IMPULSE, SEC	1000	1200
INITIAL GROSS WT, LB	620,000	520,000
THRUST, LB	62,000	52,000
TEMP, °F	5000	5700
PRESSURE, ATM	3.3	2.3
REACTOR POWER, MW	1200	1700

CS-14742

Table III

# SPECIFIC IMPULSE OF HYDROGEN

PRESSURE, 100 ATM

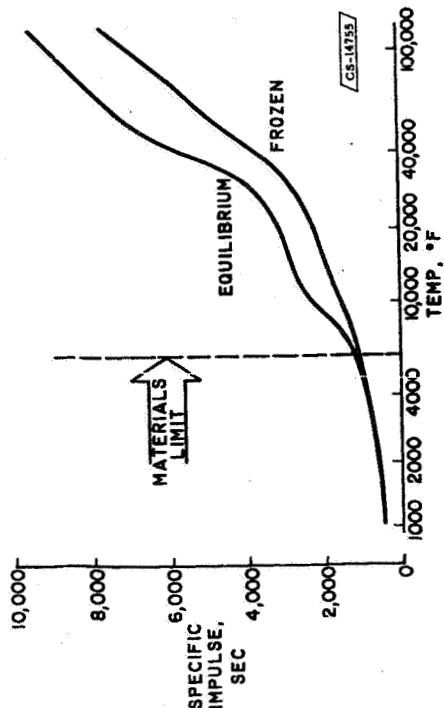


Figure 2

# NUCLEAR ROCKET MOTOR

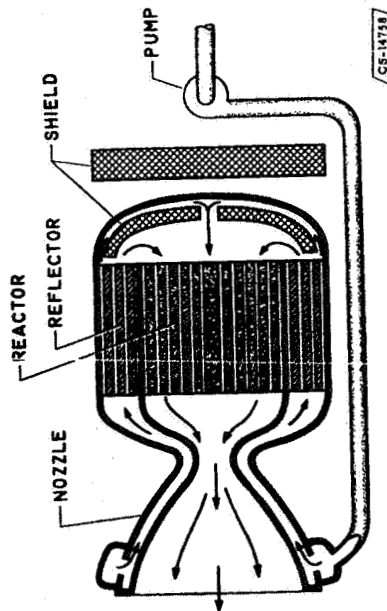


Figure 4

# NUCLEAR ROCKET

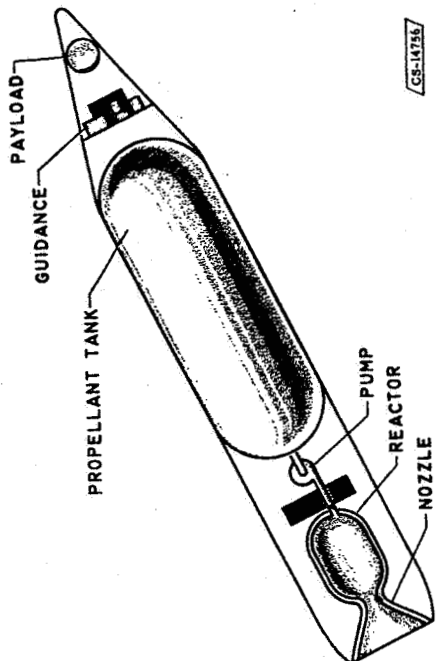


Figure 3

# MAXIMUM TEMPERATURE FOR REACTOR MATERIALS

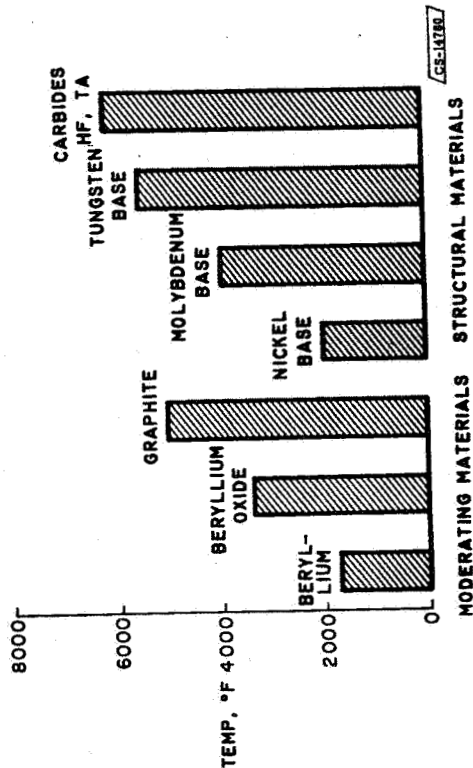
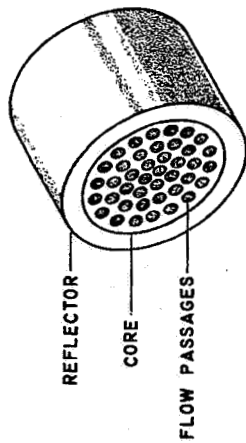


Figure 5

## NUCLEAR ROCKET REACTOR

GRAPHITE, DISPERSED URANIUM



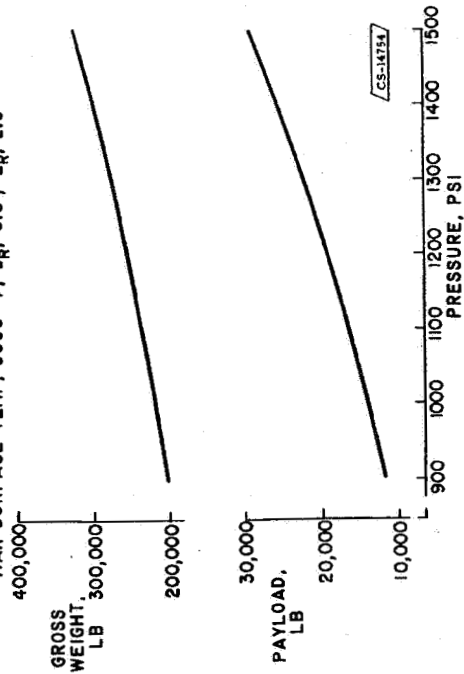
CORE DIAM., FT 3.5  
 CORE LENGTH, FT 2.8  
 CORE FREE-FLOW RATIO 0.3  
 REFLECTOR, Be, IN. 6  
 URANIUM INVESTMENT, LB 77

CS-14137

Figure 6

## EFFECT OF PRESSURE ON ROCKET PERFORMANCE

GRAPHITE, DISPERSED URANIUM, EARTH SATELLITE MISSION

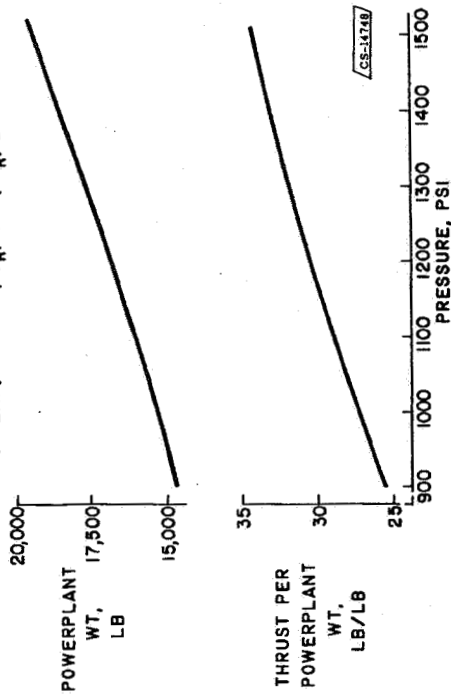
MAX SURFACE TEMP, 5000° F,  $D_R$ , 3.5',  $L_R$ , 2.8'

CS-14134

Figure 8(a)

## EFFECT OF PRESSURE ON POWERPLANT PERFORMANCE

GRAPHITE, DISPERSED URANIUM

MAX SURFACE TEMP, 5000° F,  $D_R$ , 3.5',  $L_R$ , 2.8'

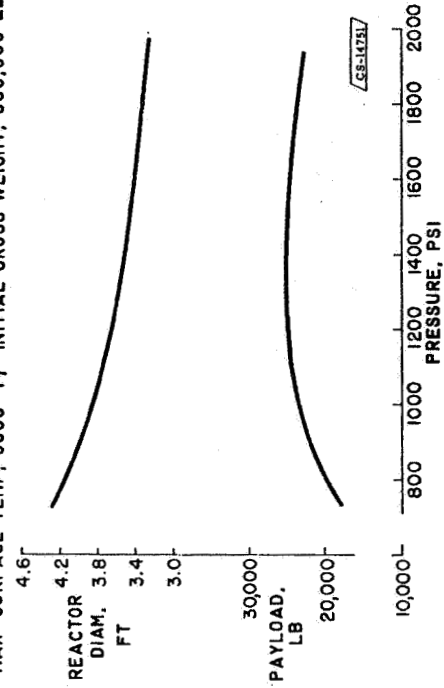
CS-14148

Figure 7

## EFFECT OF PRESSURE ON ROCKET PERFORMANCE

GRAPHITE, DISPERSED URANIUM, EARTH SATELLITE MISSION

MAX SURFACE TEMP, 5000° F, INITIAL GROSS WEIGHT, 300,000 LB



CS-14131

Figure 8(b)

# POWERPLANT PERFORMANCE COMPARISON

DISPERSED URANIUM REACTORS PRESSURE, 1200 PSI

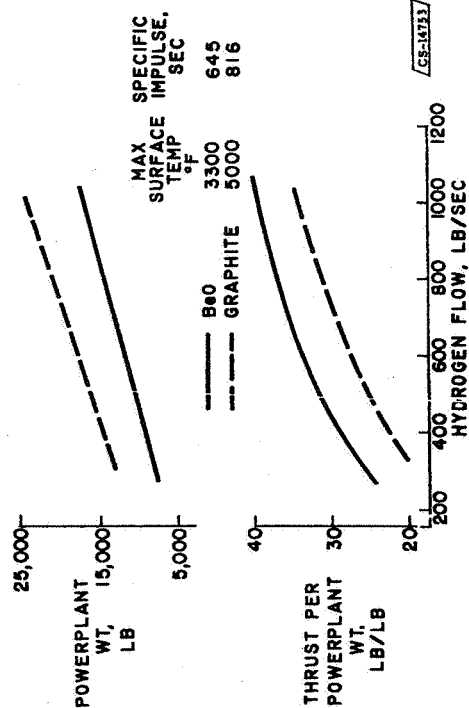


Figure 9

# POWERPLANT PERFORMANCE COMPARISON

FUEL ELEMENT, COOLED MODERATOR TYPE, PRESSURE, 1200 PSI

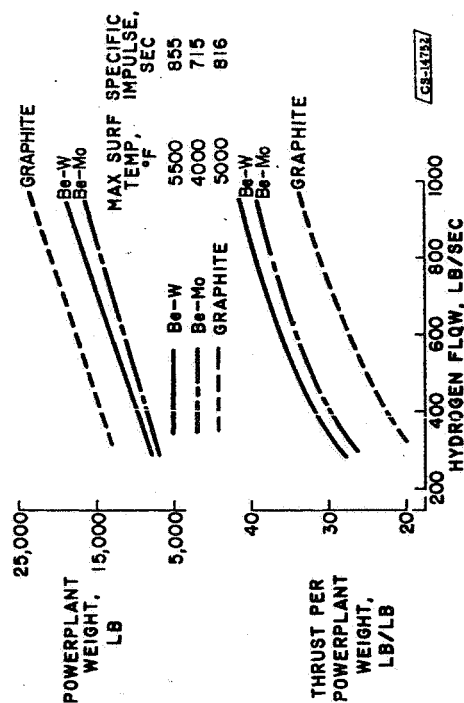


Figure 11

# NUCLEAR ROCKET MOTOR FUEL ELEMENT COOLED MODERATOR TYPE

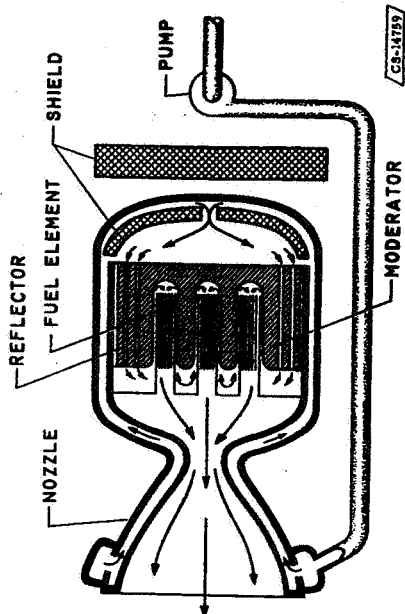


Figure 10

# SPECIFIC IMPULSE OF HYDROGEN

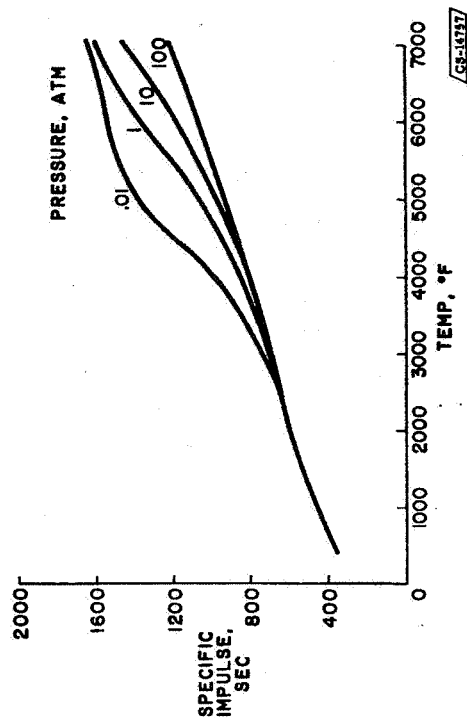


Figure 12